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12-core × 3-mode Dense Space Division Multiplexed Transmission over 40 km Employing Multi-carrier Signals with Parallel MIMO Equalization

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Abstract: We demonstrate dense SDM transmission of 20-WDM multi-carrier PDM-32QAM signals over a 40-km 12-core × 3-mode fiber with 247.9-b/s/Hz spectral efficiency. Parallel MIMO equalization enables 21-ns DMD compensation with 61 TDE taps per subcarrier.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications.

1. Introduction

Space division multiplexing (SDM) for optical fiber transmission has attracted considerable research interest over the past few years [1-9]. A number of studies have contributed to increasing the transmission capacity and spectral efficiency (SE) possible with SDM. In earlier studies, the spatial multiplicity was less than 10. This number has risen to N=19 in multi-core fiber (MCF) [2] and M=6 in few-mode fiber (FMF) transmission [3], where M and N are the number of spatial modes and cores, respectively. In our previous work [4], we demonstrated transmission with aggregate SE of 91.4 b/s/Hz over 52-km of 12-core MCF. In [5], a higher aggregate SE of 109 b/s/Hz was reported over 3-km with a hybrid 12 single-mode and two few-mode cores yielding the spatial multiplicity of 18 (=12×1+2×3), and in [6], single wavelength 2048 QAM transmission over a 12-core MCF was reported. To further increase transmission capacity and aggregate SE, it is essential to enlarge the spatial multiplicity.

In this work, we demonstrate dense space division multiplexing (DSDM) with spatial multiplicity over 30. To realize DSDM transmission, we develop a novel multi-core few-mode fiber (MC-FMF) with fan-in/fan-out (FI/FO) devices and silica planar lightwave circuit (PLC)-based spatial multi/demultiplexers (MUX/DEMUX). Moreover, we employ low-baud rate parallel signal processing with equalization of the differential mode delay (DMD) with small number of time domain equalizer (TDE) taps, to eliminate the need for DMD compensation by fiber management. We transmit 20 wavelength division multiplexed (WDM-) polarization division multiplexed (PDM-) 32QAM signals over a 12-core × 3-mode 40-km DSDM transmission fiber, and obtain the record aggregate SE of 247.9 b/s/Hz.

2. Dense space division multiplexing (DSDM)

Figure 1(a) shows the SE per core per mode of some of recent SDM WDM transmission experiments as a function of spatial multiplicity. The tilted lines plot aggregate SE. In this work, we successfully double the aggregate SE from the previous work, by utilizing the scalability of the all few-mode MCF.

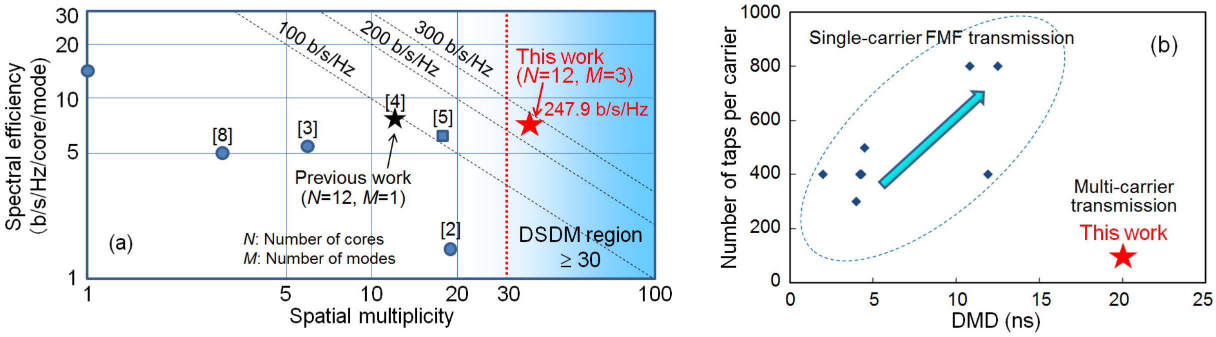

Fig. 1. (a) SE vs. spatial multiplicity, and (b) number of taps per carrier vs. DMD in recent SDM WDM experiments.

Figure 1(b) shows the number of taps per carrier required for multiple-input and multiple-output (MIMO) signal processing as a function of DMD in recent FMF transmission experiments that transmitted high baud rate signals at over 10 Gbaud. The number of taps required for MIMO equalization in such cases increases with DMD. However, increasing the number of taps causes hard convergence and unstable adaptation of the MIMO equalizer. Therefore, it is essential to compensate DMD through signal processing with a relatively small number of taps. In this work, we propose a novel MIMO signal processing technique that uses a low baud-rate multi-carrier signal, which allows us to significantly reduce the number of taps of each subcarrier required for DMD compensation compared to the equivalent single-carrier system. The total number of taps required for all subcarriers is the same as that in a single-carrier system, but MIMO equalizers can be independently implemented for each subcarrier, which eliminates the need for a huge single MIMO equalizer. The number of TDE taps required for total DMD compensation of 21 ns was reduced to 61 per subcarrier by employing our 20 × 0.525 Gbaud configuration with 20 independent parallel equalizers at the receiver side.

3. Experimental setup

Figure 2 shows the experimental setup. At the transmitters, CW optical carriers were generated; the 25 GHz-spaced even and odd channel frequencies were 12.5 GHz shifted from each other. A tunable external-cavity laser (ECL) with ~60-kHz linewidth and DFB lasers with ~2-MHz linewidth were used to generate the test channel and the remaining channels, respectively. The CW carriers (1549.1-1551.0 nm) were separately multiplexed into even-/odd-channel signals, and modulated with IQ modulators (IQMs) to create low baud-rate Nyquist-pulse-shaped 32QAM subcarrier frequency-division-multiplexing (FDM) signals. IQM driving signals were generated by DACs operated at 24.15 GS/s. The 20 FDM Nyquist-pulse-shaped 0.525-Gbaud signals with 0.01 roll-off factor were digitally generated. Each subcarrier had a digital pilot-tone [10]. The multi-level signal for each subcarrier was created by combining delayed copies of pseudo-random-binary-sequence (PRBS) of length 2^{23}-1. A 1.63 % overhead was added as the training sequence. Pre-equalization of the transmitter frequency response was employed. The even/odd channels were combined by 12.5/25 GHz interleave filters, and polarization multiplexed by a PDM emulator with 750-nsec delay. This yielded 20-ch 12.5-GHz-spaced 105-Gb/s PDM-32QAM signals, resulting in a net data rate of 86.07 Gb/s with an SE of 6.88 b/s/Hz/core/mode assuming 1.63 % training sequence and 20 % forward error correction (FEC) overhead. An optical spectrum with 20 MHz resolution is shown in Fig. 2 (b).

The signal was split into a main signal and three sets of signals by a 1 × 4 optical splitter. The main signal was further split into three, delayed by 2.94 µs for the LP_{11a} port and 5.05 µs for the LP_{11b} port relative to the LP_{01} port, pre-amplified by single-mode EDFAs, and mode-multiplexed with a low-loss silica PLC-based mode MUX [11]. The insertion loss of the PLC mode MUX/DEMUX was < 2.5 dB for the LP_{01} mode, and < 5.0 dB for the LP_{11} mode in the C-band. The wavelength, polarization, and mode multiplexed main signals were then launched into one of the few-mode core under measurement, and spatially multiplexed by a multi-core few-mode FI device. Eleven additional signals were generated by combining three sets of LP_{01} to LP_{11a} converters, LP_{01} to LP_{11b} converters, and 3 × 4 few-mode (FM) couplers, and were spatially multiplexed into the remaining 11 few-mode cores through the FI device. All 36 SDM tributaries input to the MC-FMF had their power set at -6 dBm/wavelength/core/mode.

The transmission line consisted of a spool of 40.4-km 12-core × 3-mode fiber. The few-mode cores were designed with two types of trench-assisted multi-step index profiles having different propagation constants placed next to each other in a novel square lattice arrangement, see Fig. 2(c), with a view to minimize core-to-core crosstalk.

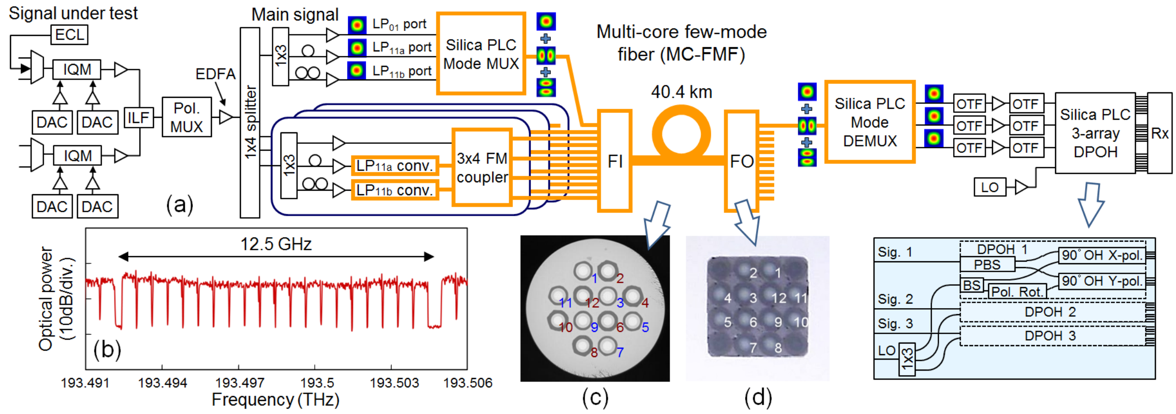

Fig. 2. (a) Experimental setup, (b) low baud-rate multi-carrier signal, (c) cross section of 12-core × 3-mode DSDM transmission fiber, and (d) cross section of multi-core few-mode FI/FO device.

The core pitch was 41 μm, the cladding diameter was 229 μm, and the dispersion of the LP_{01} mode at 1550 nm was 19.5 ps/nm/km. The C-band maximum DMD was 0.52 ns/km (21 ns total DMD), the loss at 1550 nm was 0.205 and 0.204 dB/km for the LP_{01} and LP_{11} modes, respectively, and the effective area at 1550 nm was 96 and 141 μm^2 for the LP_{01} and LP_{11} modes, respectively. The FI/FO device achieved physical contact connection of the cores between the MC-FMF and few-mode small diameter fibers arranged in a newly developed ferrule with a square hole (Fig. 2 (d)). The excess loss caused by misalignment ranged from 0.2-0.7 dB. The inter-core crosstalk and the total span loss at 1550 nm of the transmission fiber with the FI/FO devices were < -49 dB and 8.2-8.8 dB, respectively, for the LP_{01} mode, and < -42 dB and 8.9-10.6 dB, respectively, for the LP_{11} mode.

At the receiver, the core under test was selected for each measurement after spatial demultiplexing by the FO device and then mode-demultiplexed by the PLC mode DEMUX. The three received sets of signals were wavelength-demultiplexed by optical tunable filters (OTFs), and input together into a PLC 3-array integrated dual polarization optical hybrid (DPOH) module designed for 6 × 6 MIMO signal processing. A free-running ECL with a linewidth of ~70 kHz was used as the local oscillator (LO). The light input into the common LO input port was split by a 1 × 3 splitter and sent to the three LO ports, all integrated on a PLC chip on the 90 × 40 × 7 mm module.

4. DSDM transmission results

The received signals were digitized at 40 GS/s using a 12-ch digital storage oscilloscope, and stored in sets of 20M samples. In offline processing, each subcarrier was independently demodulated. Pre-convergence of adaptive signal processing consisting of 6 × 6 × 61 MIMO equalization with $T/2$-spaced tap and frequency/phase recovery, was performed utilizing training sequences and pilot-tones. Next, the adaptation algorithm was switched to decision-directed mode [10]. Differential decoding was utilized to avoid cycle slip. Bit error ratio (BER) of each mode was calculated from the sum of 20-subcarriers' symbols corresponding to 2.4M symbols. The Q-factor was calculated from the measured BER of the demodulated signals.

Figure 3 shows the measured Q-factor performance for the 20 wavelengths after 40-km PDM-32QAM signal transmission. The number of SDM tributary is determined by $(n\text{-}1)\times M+m$, where n is the core number indicated in Fig. 2(c), M=3, and m is the mode number (m=1: LP_{01}, m=2: LP_{11a}, and m=3: LP_{11b}). The inset in Fig. 3 shows the constellations of core #2, wavelength #10, subcarrier #10. The Q-factors for all 36 SDM tributaries for the 20 wavelengths were better than 7.0 dB, which exceeds the Q-limit (5.7 dB, dashed line) of the LDPC convolutional codes using layered decoding algorithm with 20 % FEC overhead.

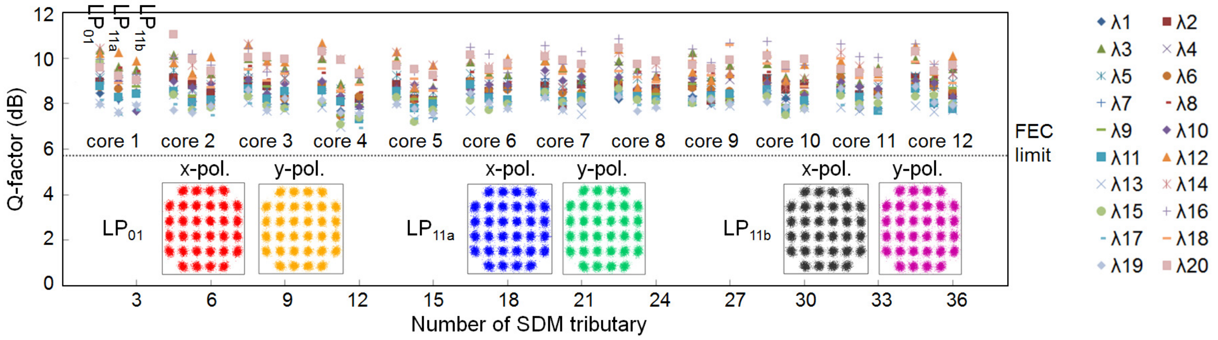

Fig. 3. Q-factors after 40-km transmission.

5. Conclusions

We have successfully transmitted dense space division multiplexing (DSDM) signals with the spatial multiplicity of 36 over 40.4 km by employing a novel 12 core × 3 mode MC-FMF with FI/FO devices, PLC mode MUX/DEMUX, and PLC 3-array DPOH for 6 × 6 MIMO signal processing. We implemented a low baud-rate multi-carrier signal transmission with parallel MIMO equalization; compensation of the DMD of 21 ns needed only 61 TDE taps per subcarrier. Using 20-WDM PDM-32QAM, our experiment achieved the highest aggregate SE of 247.9 b/s/Hz.

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